CONAHCYT
CONSEJO NACIONAL DE HUMANIDADES
CIENCIAS Y TECNOLOGÍAS

Instituto de Ciencias Nucleares UNAM

Pinning down top-quark-pair and single top-quark production with low-pileup data in ATLAS

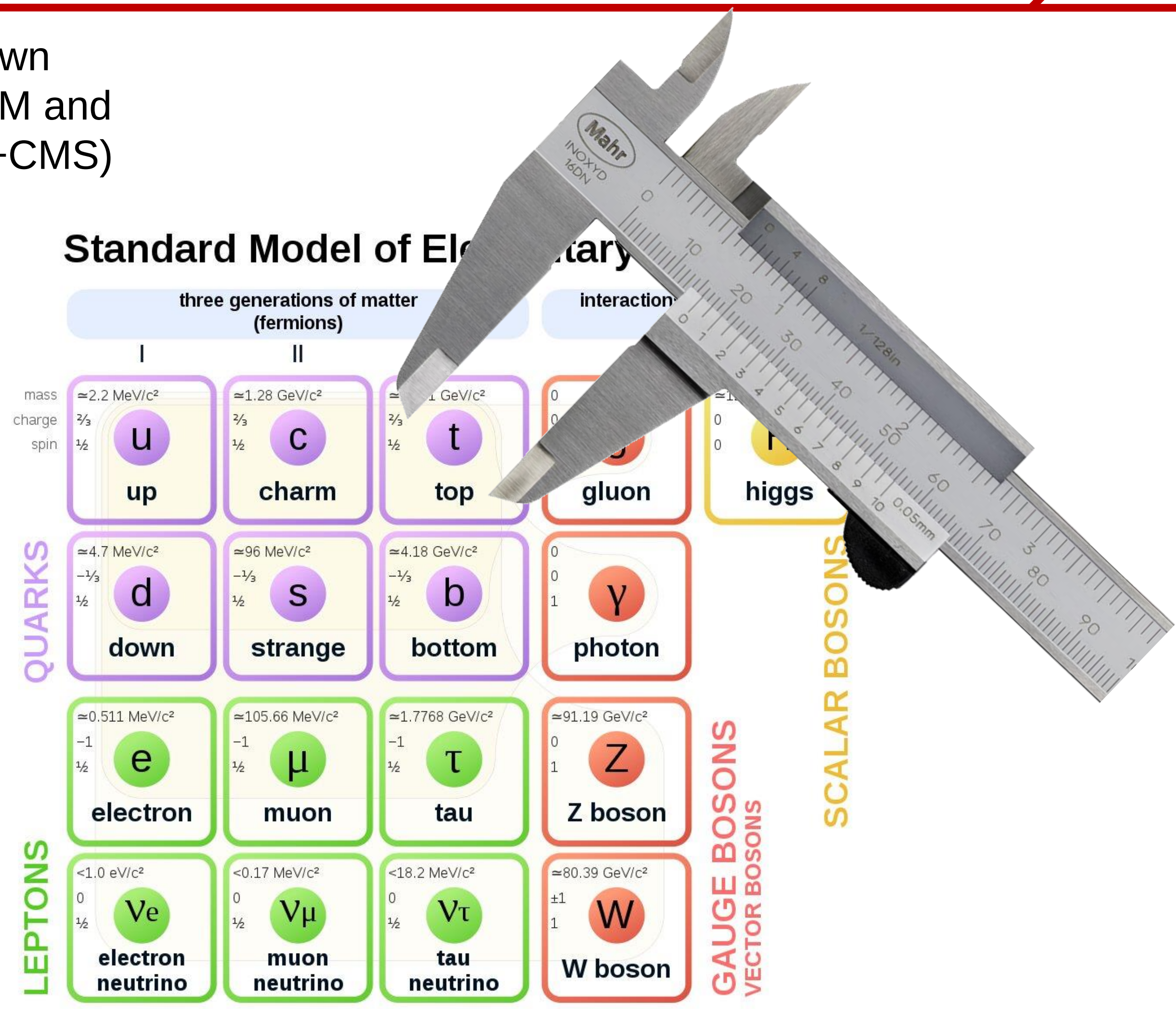
Dr. Leonid Serkin

Departamento de Física de Altas Energías
Instituto de Ciencias Nucleares (ICN-UNAM), México

21-24 May 2024, Workshop on medical and high energy physics at Sonora, Mexico

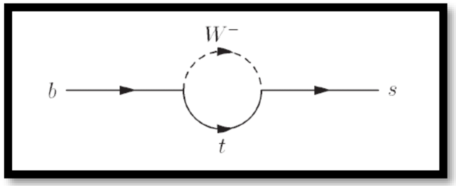
Top quark in the SM

- The top quark is the heaviest known elementary particle described by SM and has a mass of **172.5** GeV (ATLAS+CMS)



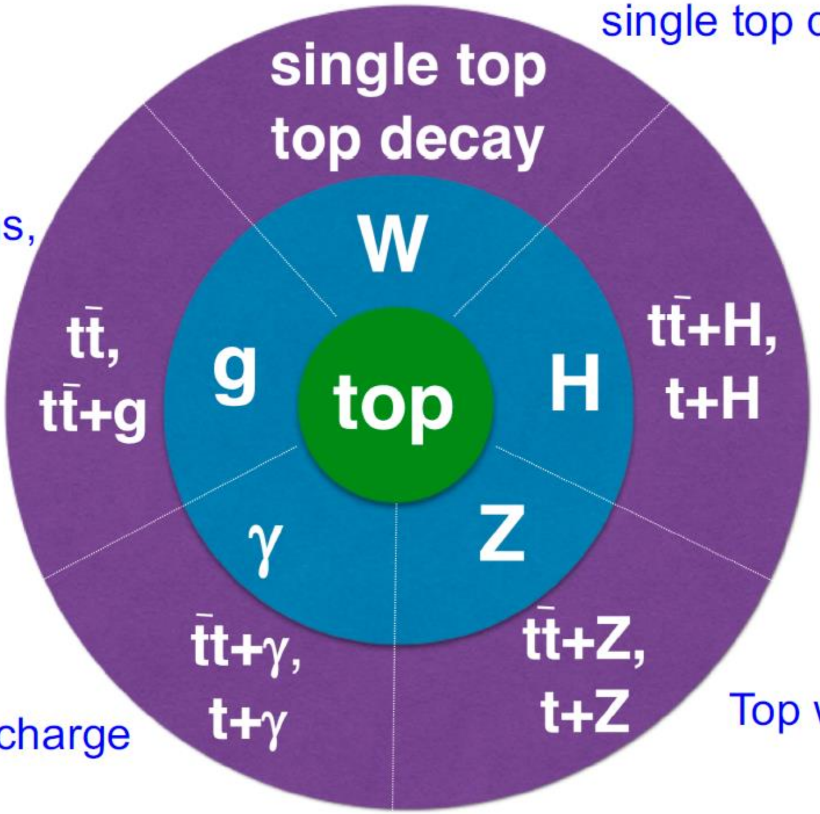
- Due to its large mass, the predicted top quark lifetime (~ 5 x 10^{-25} s) implies that it **decays before forming hadrons**

The role of the top quark



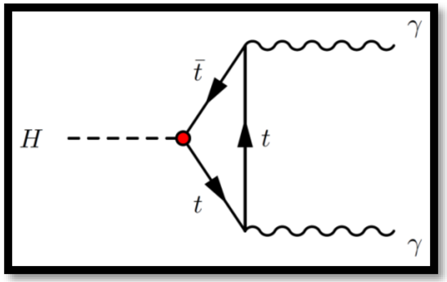
Top quark couples to other SM fields through its **gauge and Yukawa interactions.**

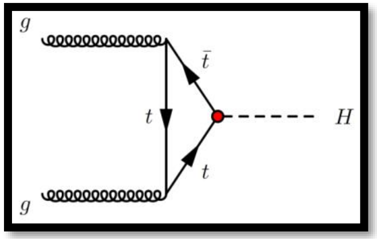
W helicity and several single top quark measurements



Differential cross-sections, spin correlations, charge asymmetry, etc.

Top Yukawa coupling



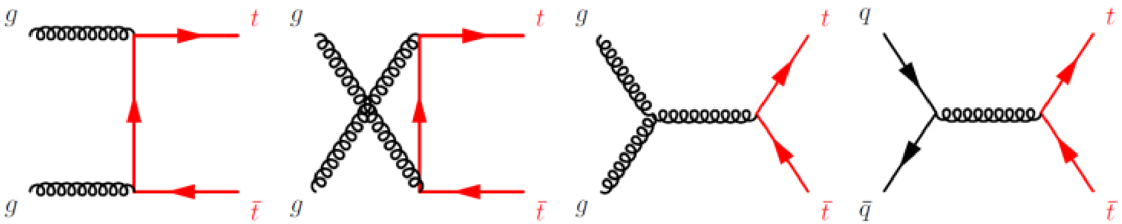


Top electric charge

Top weak isospin

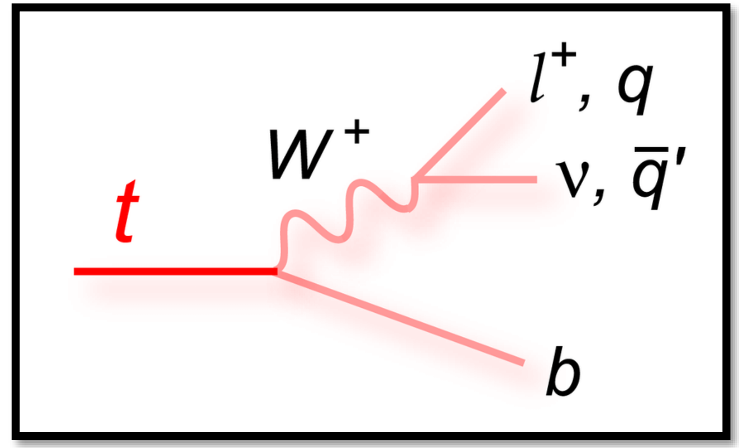
The top quark production and decay

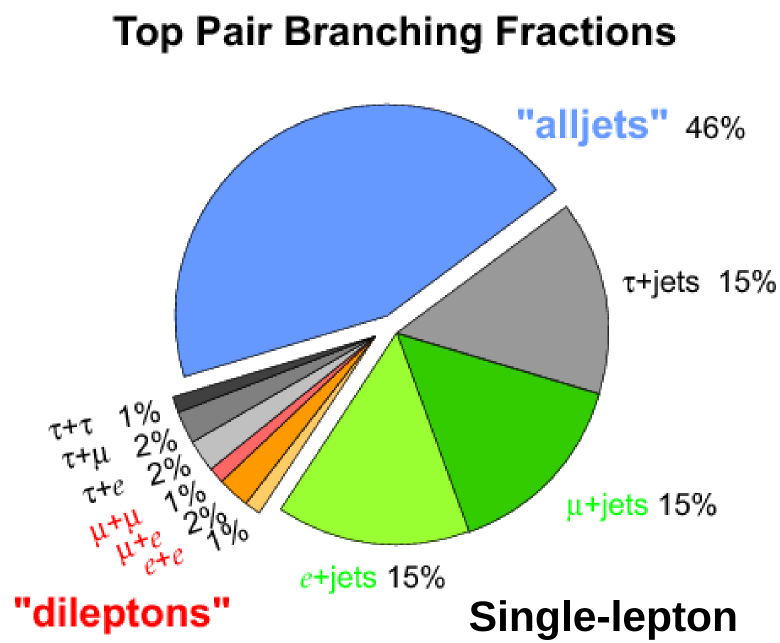
- Top quark pair production governed by strong interaction:



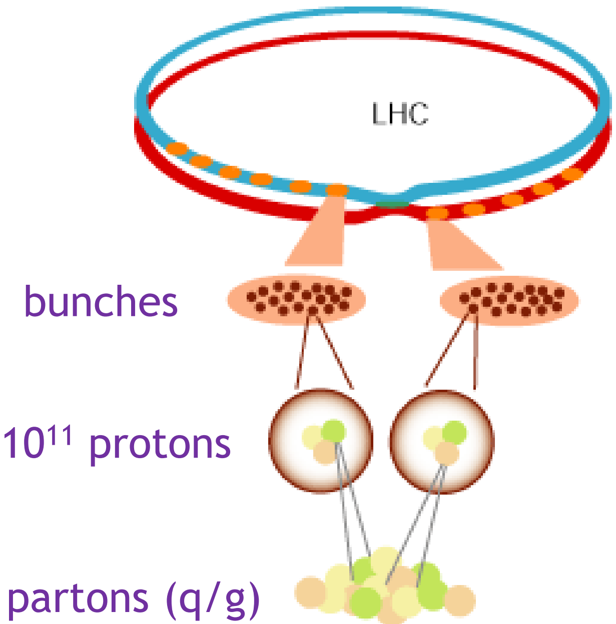
- The top quark decays almost 100% to a W-boson and b-quark ($V_{tb} \sim 1$), and the final state topology is given W-boson decays:

Decay mode	Branching fraction [%]
$W \to q\bar{q}$	67.41 ± 0.27 (6/9)
$W \to e\bar{\nu}_e$	10.71 ± 0.16 (1/9)
$W \to \mu\bar{\nu}_\mu$	10.63 ± 0.15 (1/9)
$W \to \tau\bar{\nu}_\tau$	11.38 ± 0.21 (1/9)

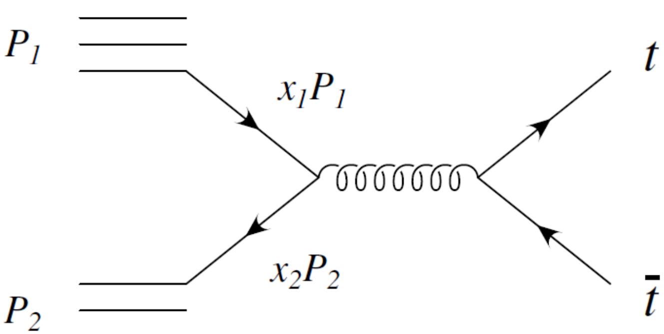




Producing top quarks at the LHC

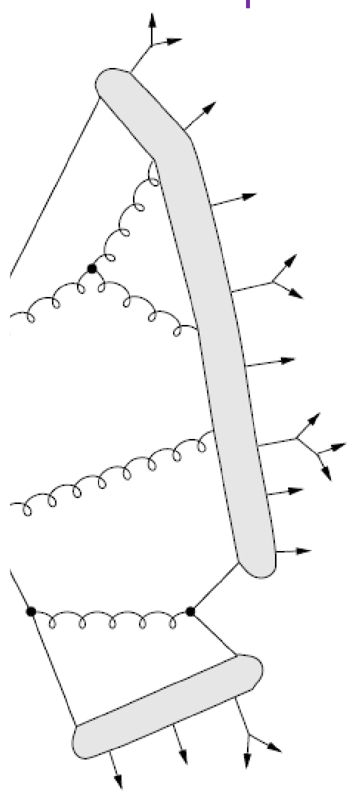


The ATLAS and CMS experiments at the LHC have accumulated millions of top quark events **(~ 500 top quark pairs per minute)**, sustained by data from the LHCb experiment in forward regions

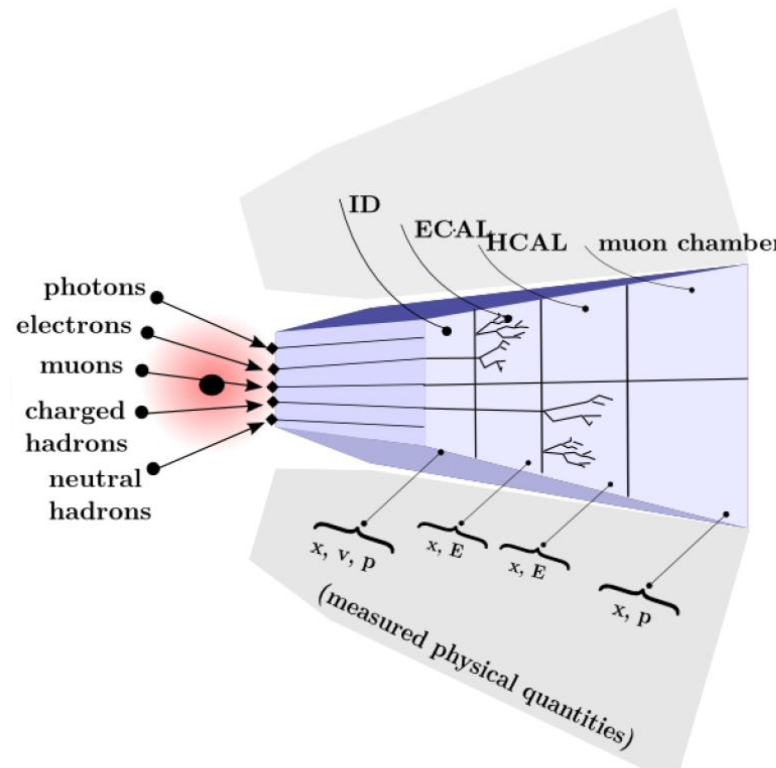


The hard interaction is described in terms of **cross-section (σ)**

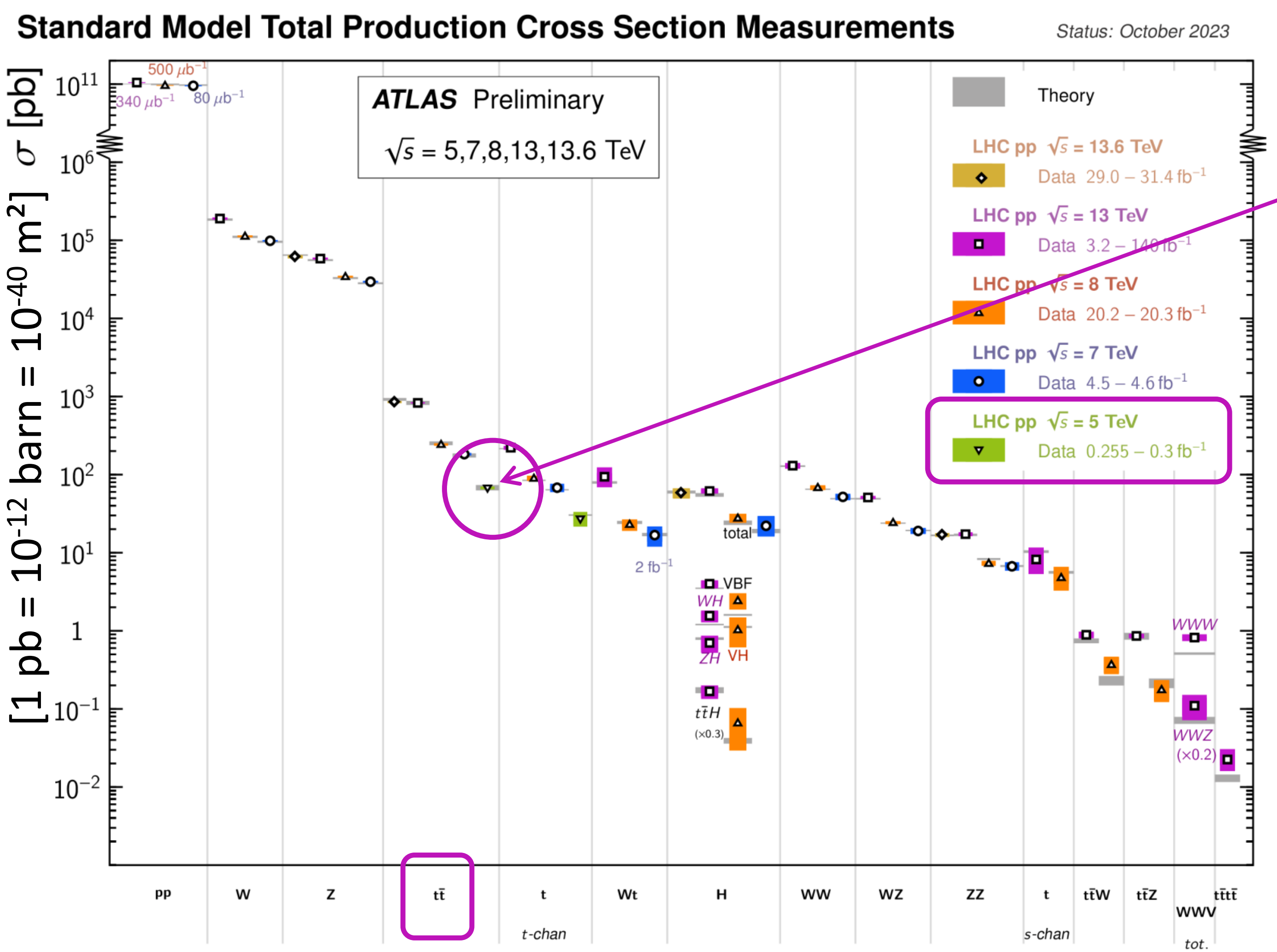
Hadronisation process

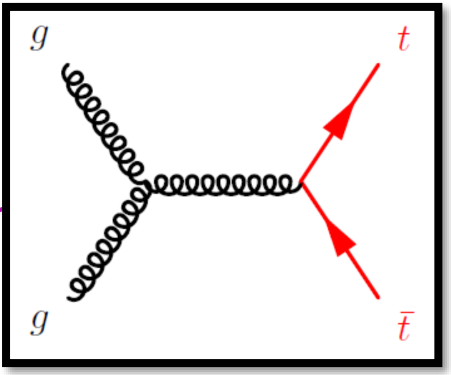


Final states are measured by different detectors



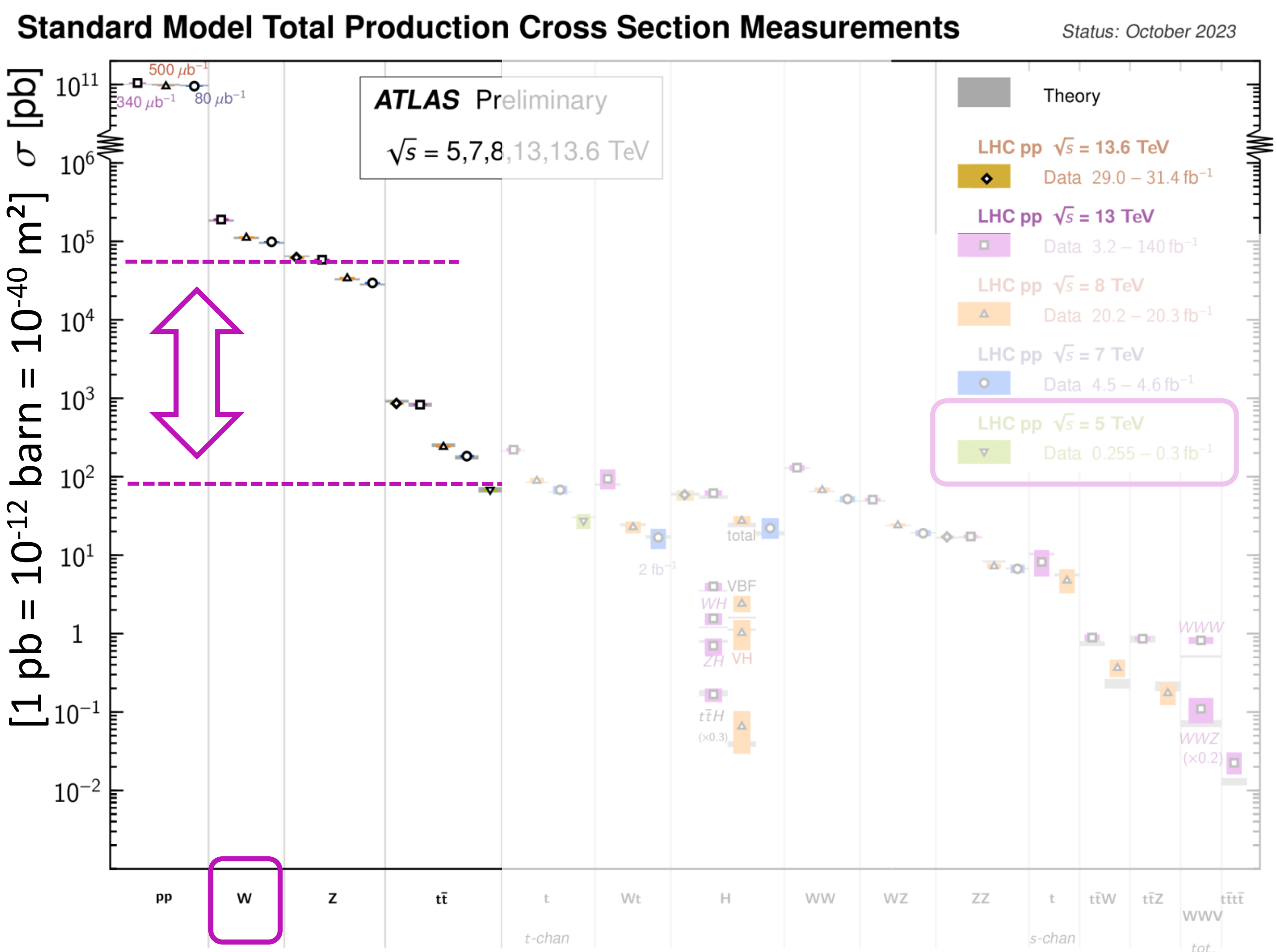
Top quark production cross-section at the LHC

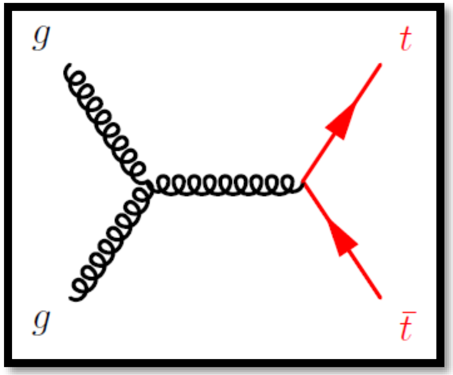




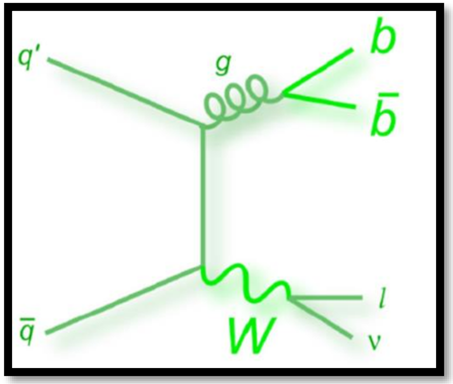
σ (top-quark-pair) with final state WbWb at 5 TeV is ~70 pb

Top quark production cross-section at the LHC



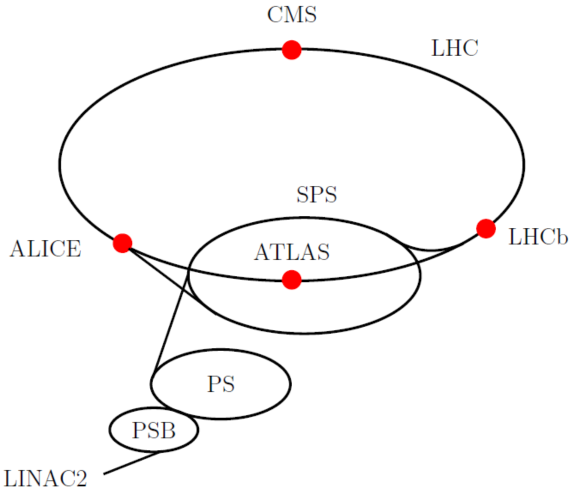


σ (top-quark-pair) with final state WbWb at 5 TeV is ~70 pb



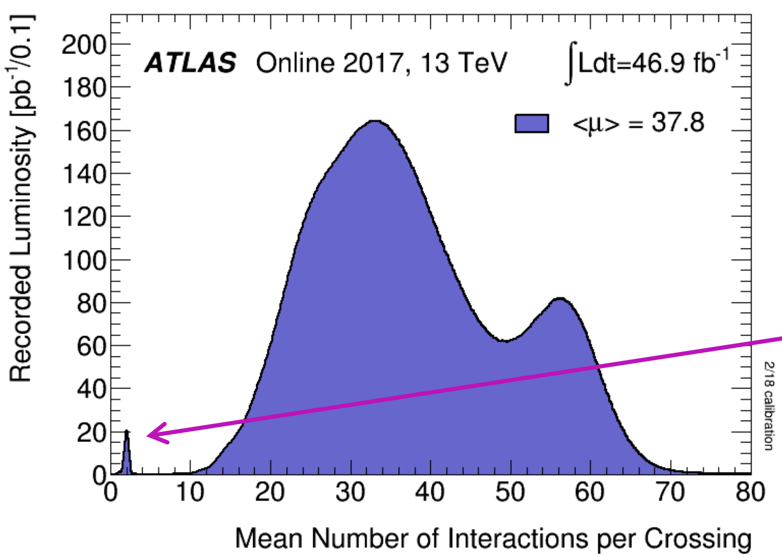
The production of a W boson in association with jets has a similar final state (Wbb) but a cross-section which is **three orders of magnitude higher**!

Low pile-up data at the LHC



- In Nov. 2017, ATLAS recorded **one week of proton-proton collisions at √s=5.02 TeV**
- Main motivation is bridging the energy gap and understand better the fundamental physics behind different operating conditions, as well as providing a proton reference sample for heavy-ion analyses

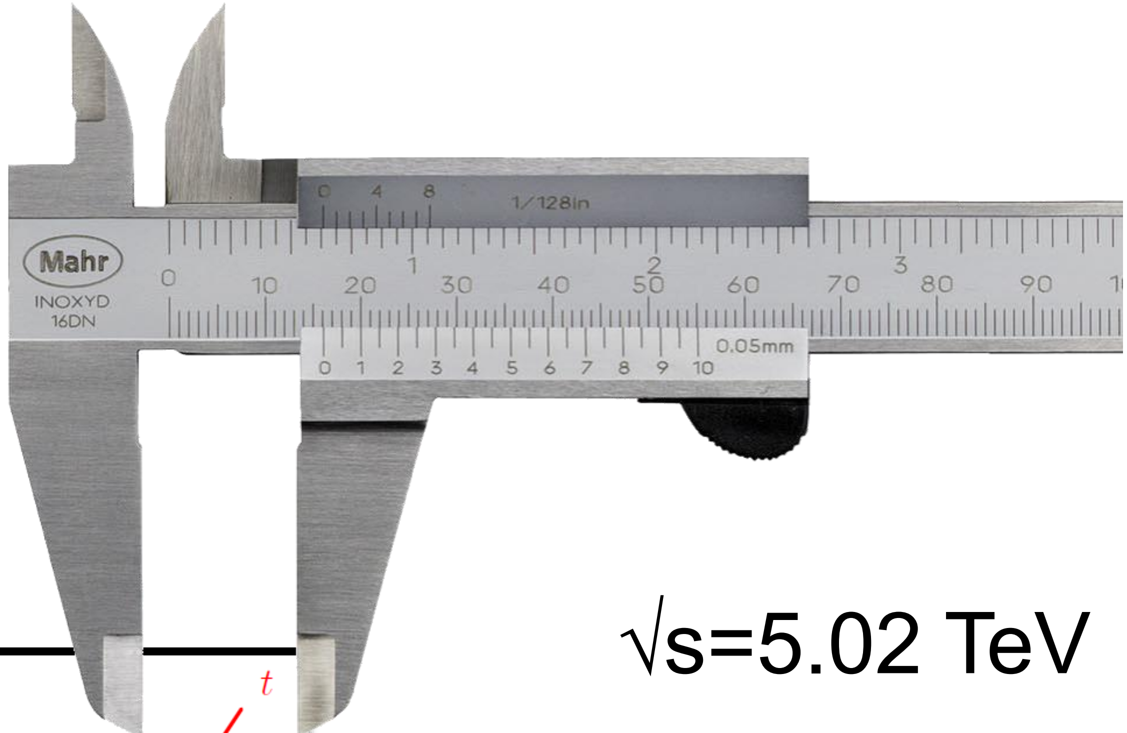
√s=5.02 TeV

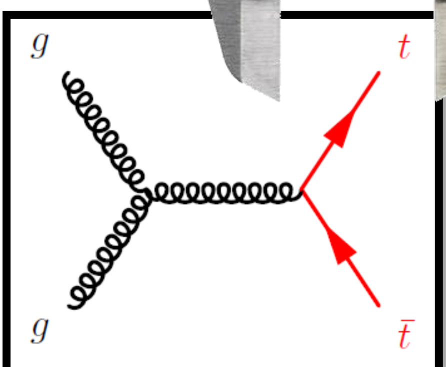


It had very low number of additional interactions per bunch crossing (pileup):
<μ> ≈ 2

- In-situ correction needed as we have lower noise thresholds compared to the "usual" high pile-up (<μ> ≈ 38) data!

Measuring σ(ttbar) at √s=5.02 TeV with ATLAS

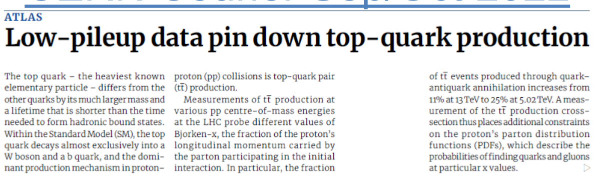




Published June 2023

[JHEP 06 (2023) 138](#)

[CERN Courier Sep/Oct 2022](#)



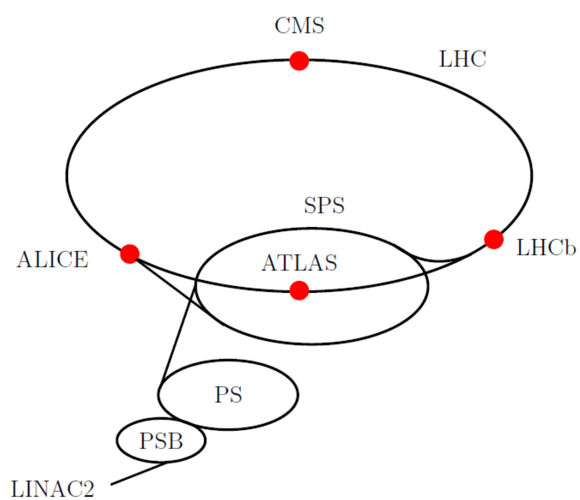
ATLAS

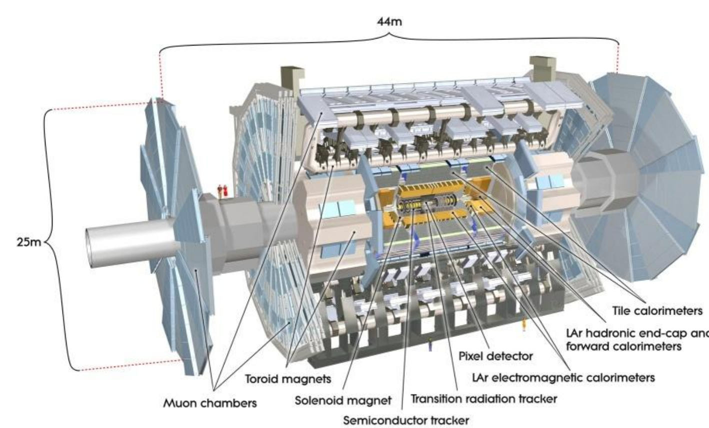
Low-pileup data pin down top-quark production

The top quark – the heaviest known elementary particle – differs from the other quarks by its much larger mass and a lifetime that is shorter than the time needed to form hadronic bound states. Within the Standard Model (SM), the top quark decays almost exclusively into a W boson and a b quark, and the dominant production mechanism in proton–proton (pp) collisions is top-quark pair ($t\bar{t}$) production.

Measurements of $t\bar{t}$ production at various pp centre-of-mass energies at the LHC probe different values of Bjorken-x, the fraction of the proton's longitudinal momentum carried by the parton participating in the initial interaction. In particular, the fraction of $t\bar{t}$ events produced through quark–antiquark annihilation increases from 11% at 13 TeV to 25% at 5.02 TeV. A measurement of the $t\bar{t}$ production cross-section thus places additional constraints on the proton's parton distribution functions (PDFs), which describe the probabilities of finding quarks and gluons at particular x values.

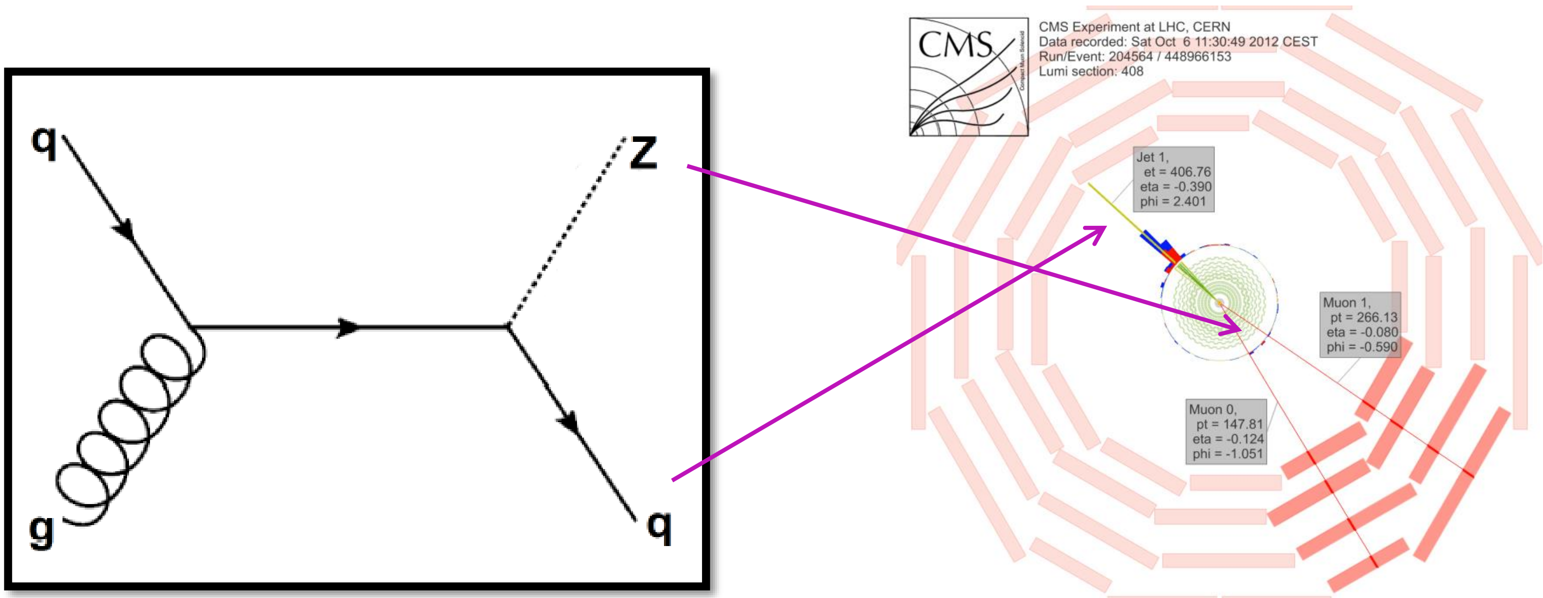
√s=5.02 TeV





Jet re-calibration at √s=5.02 TeV

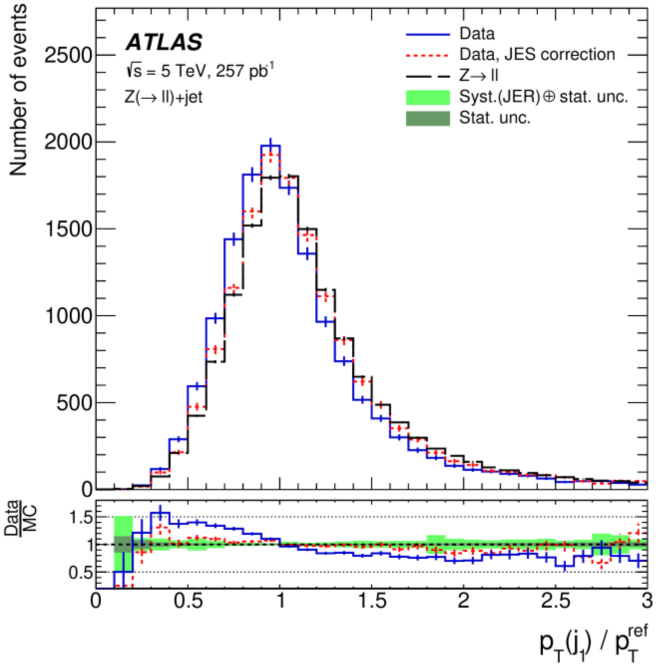
- Dedicated jet-energy scale and resolution calibration performed.
- The technique called "**Z+jet balance**" exploits the transverse momentum balance between the jet recoiling a Z-boson (that decays to electrons or muons)
- To first order, the sum of all transverse momenta in an event at ATLAS should be zero. A non-zero sum of pT in an event from a process containing jets could indicate a flaw with the jet energy calibration.

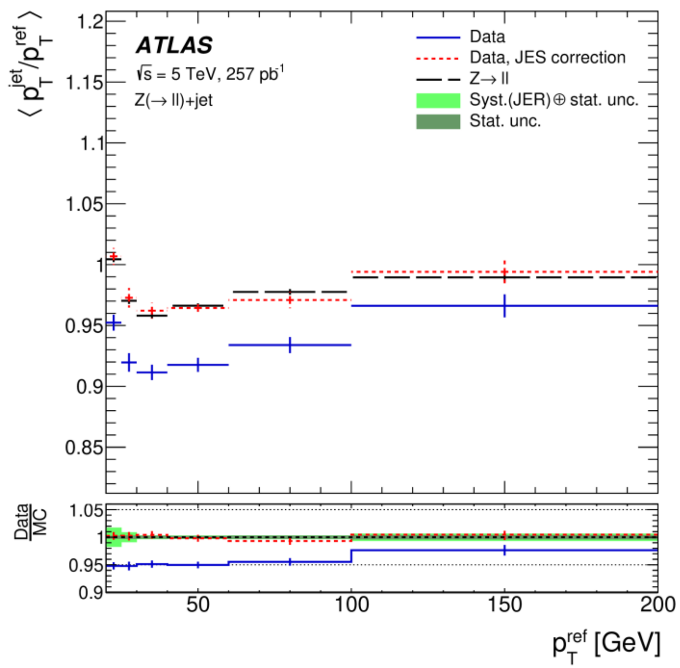


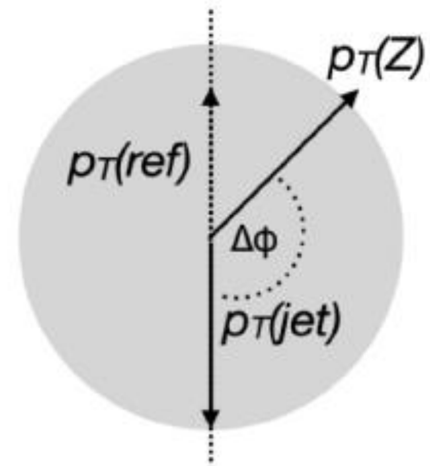
Jet re-calibration at $\sqrt{s}$=5.02 TeV

- Select **same-flavour opposite-sign lepton pair** such as the dilepton mass is between 81 < m(ll) < 101 GeV (the Z-boson candidates)

- Look for a **recoiling jet**, i.e. events with a back-to-back topology of jet wrt. to the Z-boson (azimuth Δφ > 2.8)





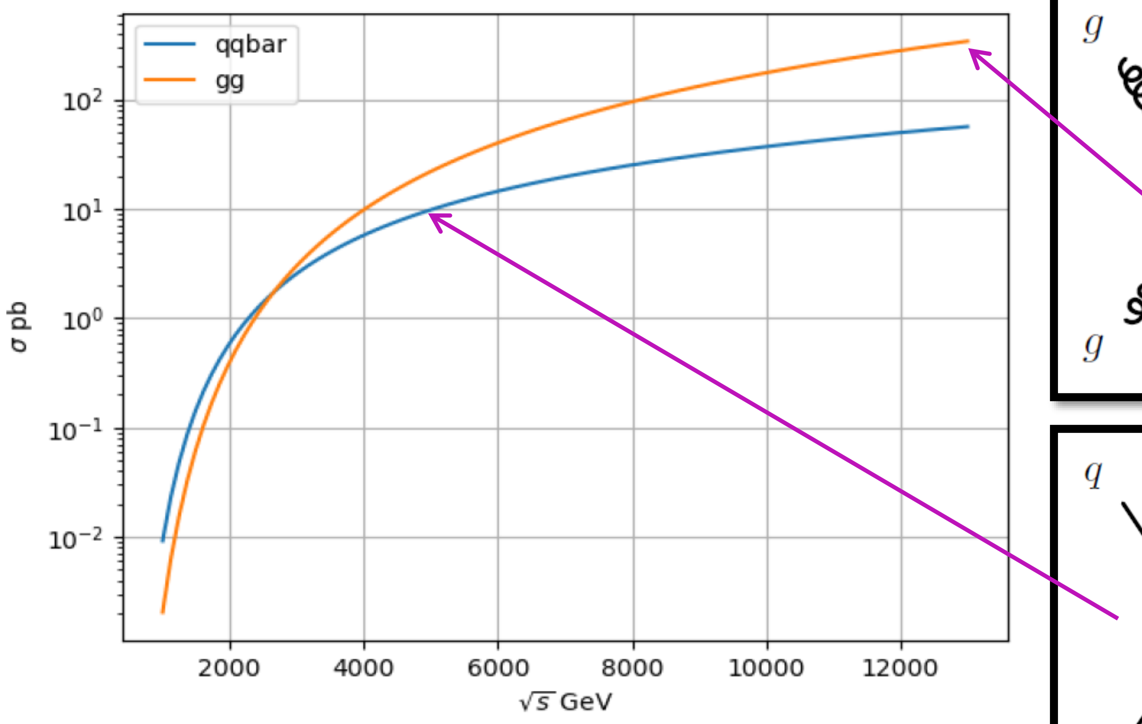


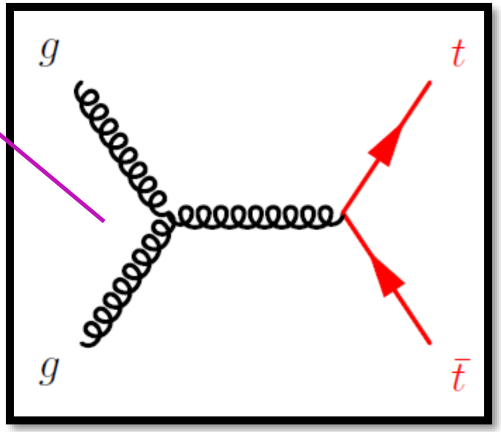
$p_T^{ref} = p_T(Z) * |\cos \Delta\varphi(Z, j_1)|$

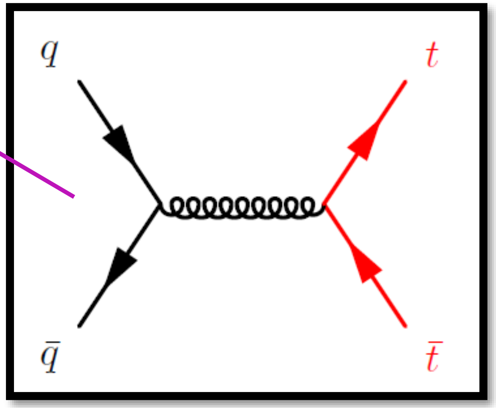
- Measure pT(reference) and pT(jet) / pT(reference) in data and in MC simulations: **must be balanced in the transverse plane**!

ttbar at √s=5.02 TeV: qqbar or gg?

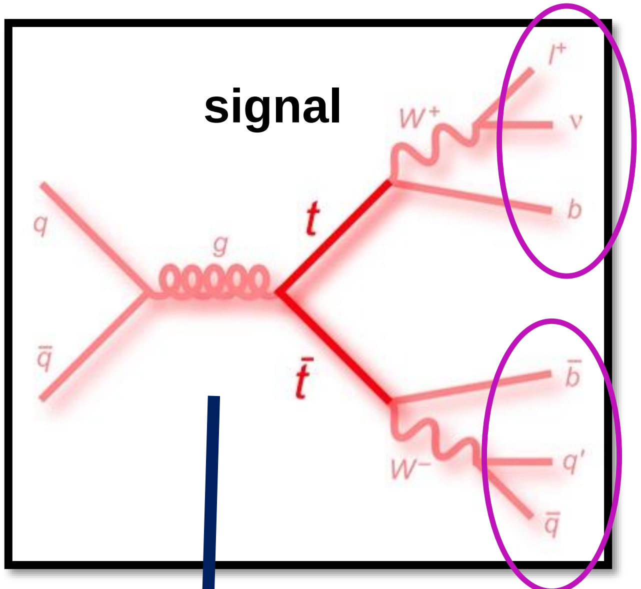
- Unique opportunity to study top-quark production at a previously unexplored energy in ATLAS:
  - ✓ **25% of qqbar-initiated** events (at LO), compared to 11% at 13 TeV



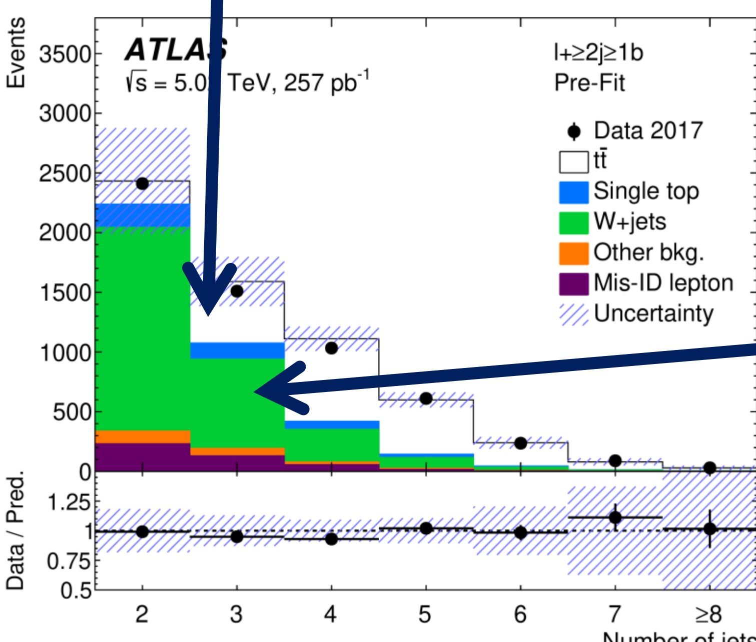


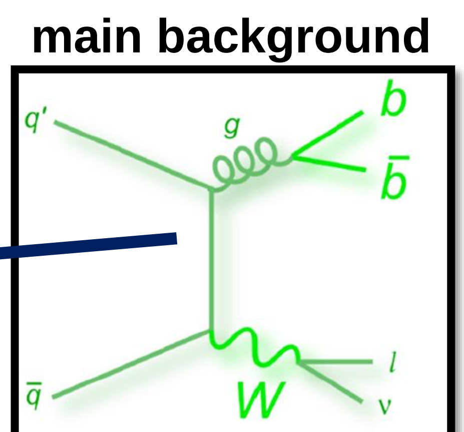


Finding top quarks in the single-lepton channel



- The single-lepton final state arising from ttbar decay is characterised by **one charged lepton, one neutrino, and at least four jets, out of which two are b-tagged.**
- First, define a trigger to remove different overwhelming background, i.e. select events that pass either a single-electron or a single-muon trigger.
- Select events that contain exactly one electron or muon candidate with pT > 25 GeV, ≥ 2 jets, 1 or 2 b-jets with pT > 20 GeV, and MET > 30 GeV





- **Monte Carlo (MC)** simulated event samples are used to develop the analysis procedures, evaluate signal and background contributions, and compare the predicted distributions with data.

ttbar at √s=5.02 TeV: single-lepton channel

- Events passing the selection requirements were further **split into six orthogonal regions** based on number of jets and b-tagged jets

Region name	Jet multiplicity	b-jet multiplicity
ℓ+2j≥1b	2	≥ 1
ℓ+3j 1b	3	1
ℓ+3j 2b	3	2
ℓ+≥4j 1b	≥ 4	1
ℓ+4j 2b	4	2
ℓ+≥5j 2b	≥ 5	2

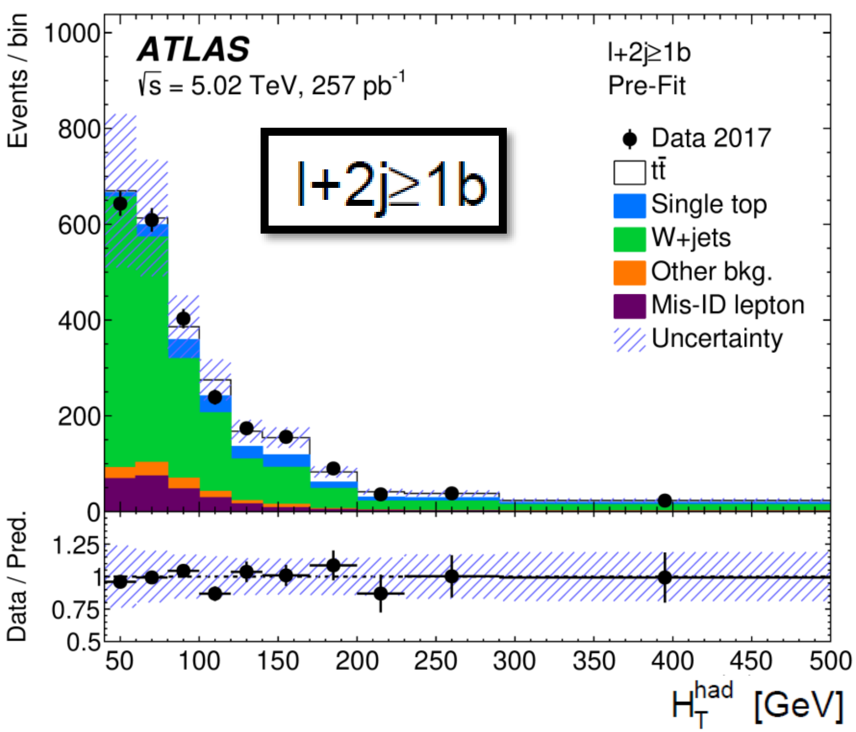
	$\ell+2j \geq 1b$	$\ell+3j\ 1b$	$\ell+3j\ 2b$	$\ell+\geq 4j\ 1b$	$\ell+4j\ 2b$	$\ell+\geq 5j\ 2b$
$t\bar{t}$	194 ± 27	310 ± 33	199 ± 24	690 ± 60	318 ± 32	380 ± 60
Single top	195 ± 22	98 ± 12	38 ± 5	67 ± 9	22 ± 4	15.9 ± 2.7
W+ jets	1700 ± 400	690 ± 210	58 ± 23	350 ± 120	30 ± 14	19 ± 10
Other bkg.	110 ± 40	55 ± 23	7.2 ± 3.0	29 ± 12	3.5 ± 1.5	3.7 ± 1.7
Misidentified leptons	250 ± 130	110 ± 60	10 ± 5	60 ± 30	6 ± 3	8 ± 5
Total	2500 ± 400	1260 ± 210	312 ± 34	1200 ± 160	380 ± 40	430 ± 70
Data	2411	1214	293	1135	375	444

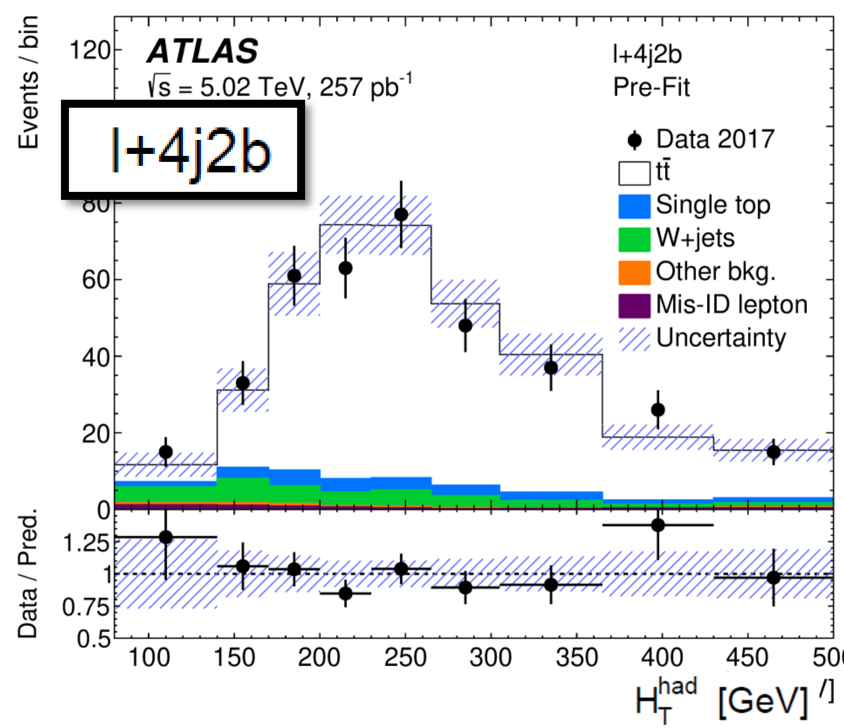
ttbar at $\sqrt{s}$=5.02 TeV: single-lepton channel

- Events passing the selection requirements were further split into six orthogonal regions based on number of jets and b-tagged jets

  ✓ This created **subsamples with different levels of signal and background,** each having an excellent agreement of rates and shapes

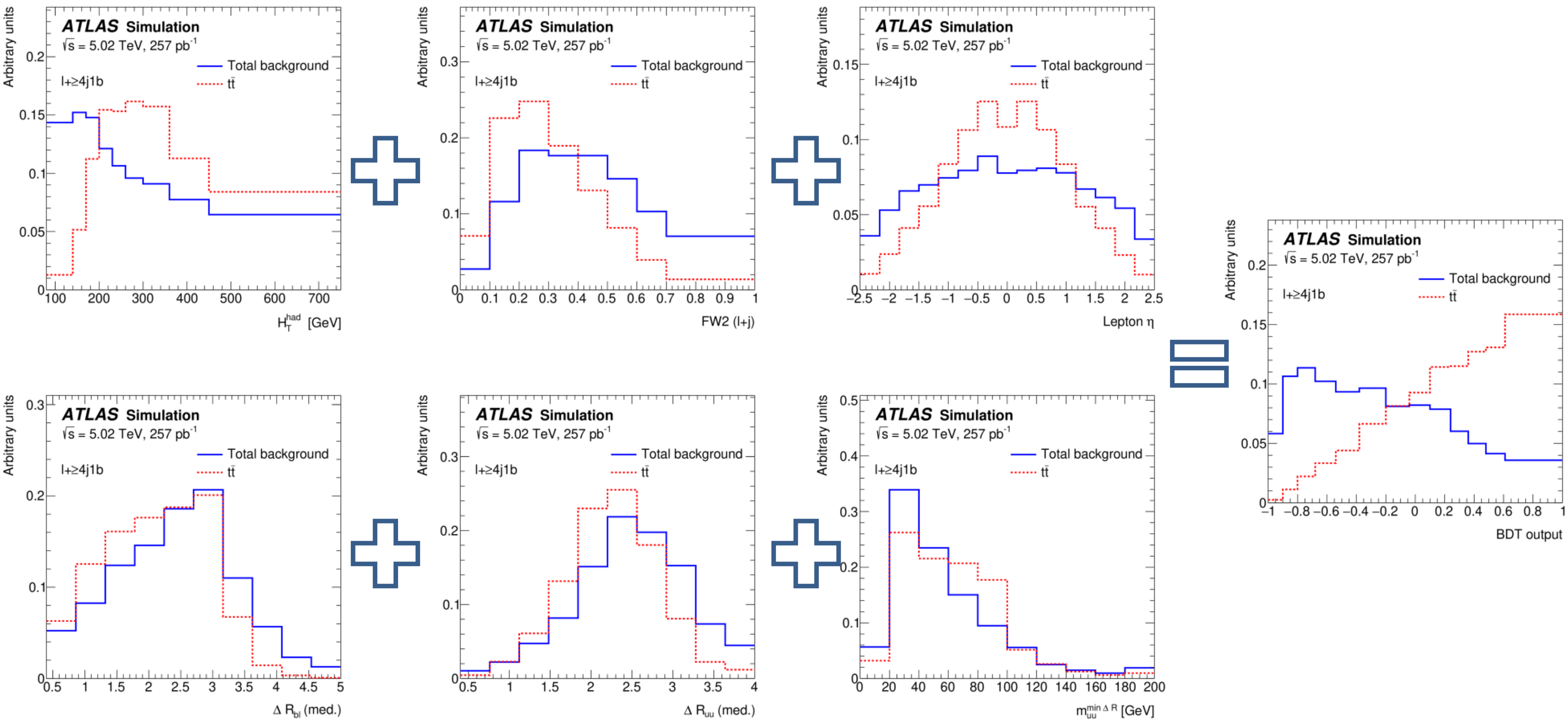
Region name	Jet multiplicity	b-jet multiplicity
ℓ+2j≥1b	2	≥ 1
ℓ+3j 1b	3	1
ℓ+3j 2b	3	2
ℓ+≥4j 1b	≥ 4	1
ℓ+4j 2b	4	2
ℓ+≥5j 2b	≥ 5	2





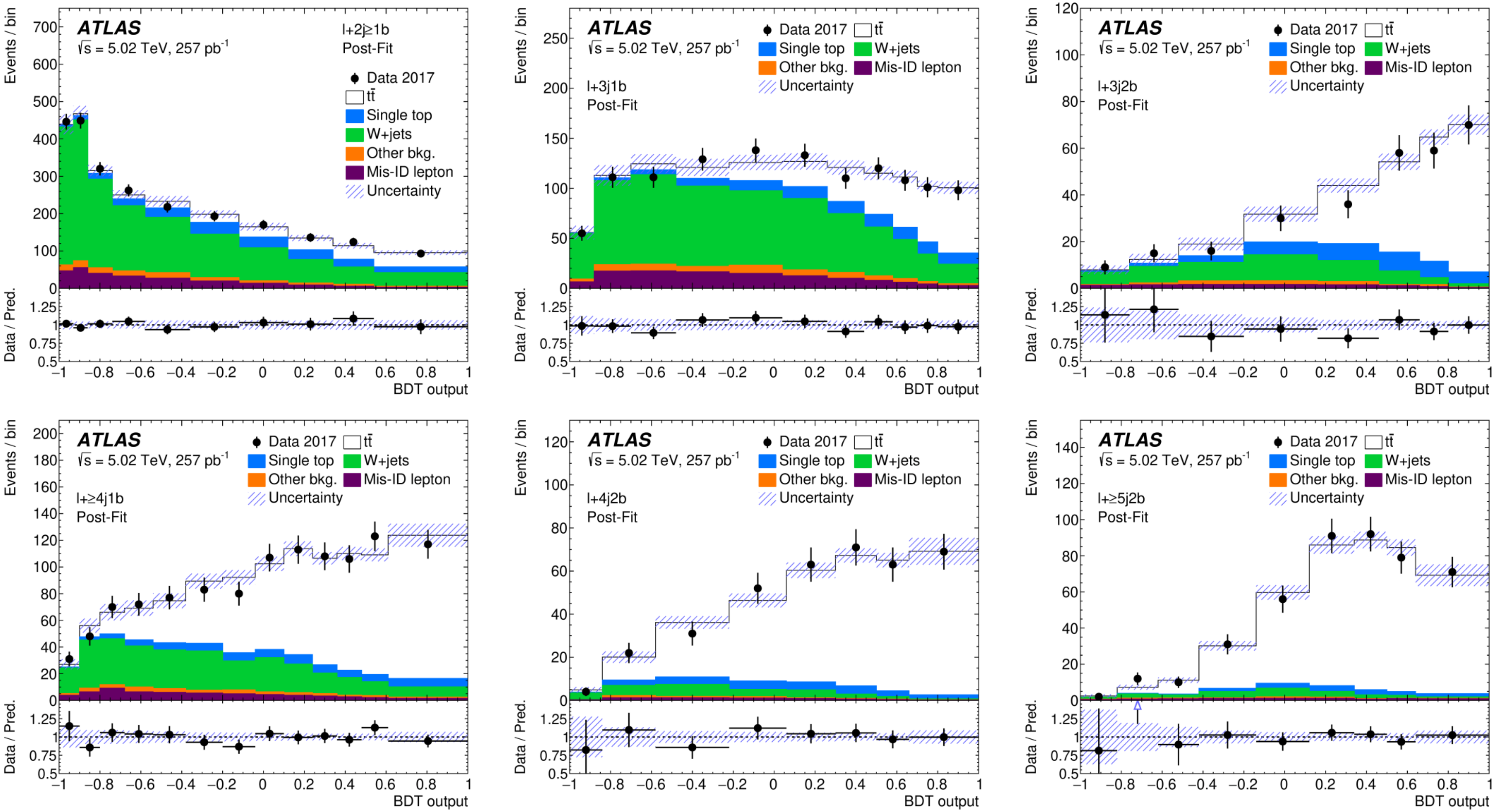
ttbar at √s=5.02 TeV: signal vs background

- Boosted Decision Trees (BDT) are used **to separate the signal from background** events and extract the ttbar production cross-section
- 6 variables chosen to have good signal-to-background separation and in combination provided greater separation than other choices



ttbar at √s=5.02 TeV: BDT in single-lepton channel

- Compare the shapes of the BDT outputs in each region with data
- Interpreted by a **statistical model** that employs the expected distributions for both the background and signal contributions in the six regions.



ttbar at √s=5.02 TeV: uncertainties

Category	$\delta\sigma_{t\bar{t}}$ [%] Dilepton	Single lepton
$t\bar{t}$ generator†	1.2	1.0
$t\bar{t}$ hadronisation*,†	0.3	0.9
$t\bar{t}$ h_{damp} and scale variations†	1.0	1.1
$t\bar{t}$ parton-distribution functions†	0.2	0.2
Single-top background	1.1	0.8
W/Z+jets background*	0.8	2.4
Diboson background	0.3	0.1
Misidentified leptons*	0.7	0.3
Electron identification/isolation	0.8	1.2
Electron energy scale/resolution	0.1	0.1
Muon identification/isolation	0.6	0.2
Muon momentum scale/resolution	0.1	0.1
Lepton-trigger efficiency	0.2	0.9
Jet-energy scale/resolution	0.1	1.1
$\sqrt{s}$ = 5.02 TeV JES correction	0.1	0.6
Jet-vertex tagging	< 0.1	0.2
Flavour tagging	0.1	1.1
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.1	0.4
Simulation statistical uncertainty*	0.2	0.6
Data statistical uncertainty*	6.8	1.3
Total systematic uncertainty	3.1	4.2
Integrated luminosity	1.8	1.6
Beam energy	0.3	0.3
Total uncertainty	7.5	4.5

- Largest uncertainties: luminosity (1.6%), signal and background modelling, object reconstruction
- Dilepton measurement: 6.8% data statistical uncertainty
- Single-lepton: 4.2% total systematic uncertainty and 1.3% data statistical

ttbar at √s=5.02 TeV: uncertainties

Category	$\delta\sigma_{t\bar{t}}$ [%] Dilepton	Single lepton	Combination
$t\bar{t}$ generator†	1.2	1.0	0.8
$t\bar{t}$ hadronisation*,†	0.3	0.9	0.7
$t\bar{t}$ h_{damp} and scale variations†	1.0	1.1	0.8
$t\bar{t}$ parton-distribution functions†	0.2	0.2	0.2
Single-top background	1.1	0.8	0.6
W/Z+jets background*	0.8	2.4	1.8
Diboson background	0.3	0.1	< 0.1
Misidentified leptons*	0.7	0.3	0.3
Electron identification/isolation	0.8	1.2	0.8
Electron energy scale/resolution	0.1	0.1	< 0.1
Muon identification/isolation	0.6	0.2	0.3
Muon momentum scale/resolution	0.1	0.1	0.1
Lepton-trigger efficiency	0.2	0.9	0.7
Jet-energy scale/resolution	0.1	1.1	0.8
$\sqrt{s}$ = 5.02 TeV JES correction	0.1	0.6	0.5
Jet-vertex tagging	< 0.1	0.2	0.2
Flavour tagging	0.1	1.1	0.8
$E_{\text{T}}^{\text{miss}}$	0.1	0.4	0.3
Simulation statistical uncertainty*	0.2	0.6	0.5
Data statistical uncertainty*	6.8	1.3	1.3
Total systematic uncertainty	3.1	4.2	3.7
Integrated luminosity	1.8	1.6	1.6
Beam energy	0.3	0.3	0.3
Total uncertainty	7.5	4.5	3.9

- **Combination** of a cut-and-count dilepton result with a binned PLL fit in single-lepton channel:
  - ✓ Traditional methods like BLUE do not consider post-fit correlations
  - ✓ Using Convino tool (Eur. Phys. J. C(2017) 77 792)
  - ✓ Minimising a χ^2 with 3 terms:

$$\chi^2 = \sum_{\alpha} \left(\chi^2_{s,\alpha} + \chi^2_{u,\alpha} \right) + \chi^2_p$$

$\chi^2_{s,\alpha}$ - the result of each measurement α and its statistical uncertainty

$\chi^2_{u,\alpha}$ - correlations between syst. uncert. and constraints on them from the data for each α

χ^2_p - correlation assumptions between uncertainties of two measurements

ttbar at √s=5.02 TeV: uncertainties

Category	$\delta\sigma_{t\bar{t}}$ [%] Dilepton	Single lepton	Combination
$t\bar{t}$ generator†	1.2	1.0	0.8
$t\bar{t}$ hadronisation*,†	0.3	0.9	0.7
$t\bar{t}$ h_{damp} and scale variations†	1.0	1.1	0.8
$t\bar{t}$ parton-distribution functions†	0.2	0.2	0.2
Single-top background	1.1	0.8	0.6
W/Z+jets background*	0.8	2.4	1.8
Diboson background	0.3	0.1	< 0.1
Misidentified leptons*	0.7	0.3	0.3
Electron identification/isolation	0.8	1.2	0.8
Electron energy scale/resolution	0.1	0.1	< 0.1
Muon identification/isolation	0.6	0.2	0.3
Muon momentum scale/resolution	0.1	0.1	0.1
Lepton-trigger efficiency	0.2	0.9	0.7
Jet-energy scale/resolution	0.1	1.1	0.8
$\sqrt{s}$ = 5.02 TeV JES correction	0.1	0.6	0.5
Jet-vertex tagging	< 0.1	0.2	0.2
Flavour tagging	0.1	1.1	0.8
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.1	0.4	0.3
Simulation statistical uncertainty*	0.2	0.6	0.5
Data statistical uncertainty*	6.8	1.3	1.3
Total systematic uncertainty	3.1	4.2	3.7
Integrated luminosity	1.8	1.6	1.6
Beam energy	0.3	0.3	0.3
Total uncertainty	7.5	4.5	3.9

- Post-fit uncertainty correlations **accounted** for in the combination
- **Priors** for the correlations split in 3 categories:

unique* (uncorrelated),

1-to-1 (fully correlated)

1-to-many† (i.e. separate NPs in one channel), investigated using different correlations

ttbar at √s=5.02 TeV: uncertainties

Category	$\delta\sigma_{t\bar{t}}$ [%] Dilepton	Single lepton	Combination
$t\bar{t}$ generator†	1.2	1.0	0.8
$t\bar{t}$ hadronisation*,†	0.3	0.9	0.7
$t\bar{t}$ h_{damp} and scale variations†	1.0	1.1	0.8
$t\bar{t}$ parton-distribution functions†	0.2	0.2	0.2
Single-top background	1.1	0.8	0.6
W/Z+jets background*	0.8	2.4	1.8
Diboson background	0.3	0.1	< 0.1
Misidentified leptons*	0.7	0.3	0.3
Electron identification/isolation	0.8	1.2	0.8
Electron energy scale/resolution	0.1	0.1	< 0.1
Muon identification/isolation	0.6	0.2	0.3
Muon momentum scale/resolution	0.1	0.1	0.1
Lepton-trigger efficiency	0.2	0.9	0.7
Jet-energy scale/resolution	0.1	1.1	0.8
$\sqrt{s}$ = 5.02 TeV JES correction	0.1	0.6	0.5
Jet-vertex tagging	< 0.1	0.2	0.2
Flavour tagging	0.1	1.1	0.8
E_T^{miss}	0.1	0.4	0.3
Simulation statistical uncertainty*	0.2	0.6	0.5
Data statistical uncertainty*	6.8	1.3	1.3
Total systematic uncertainty	3.1	4.2	3.7
Integrated luminosity	1.8	1.6	1.6
Beam energy	0.3	0.3	0.3
Total uncertainty	7.5	4.5	3.9

- Largest uncertainties: luminosity (1.6%), signal and background modelling, object reconstruction
- Single-lepton: 4.2% total systematic uncertainty and 1.3% data statistical
- Dilepton measurement: 6.8% data statistical uncertainty
- **Combination of both single-lepton and dilepton channels leads to a final uncertainty of just 3.9%.**

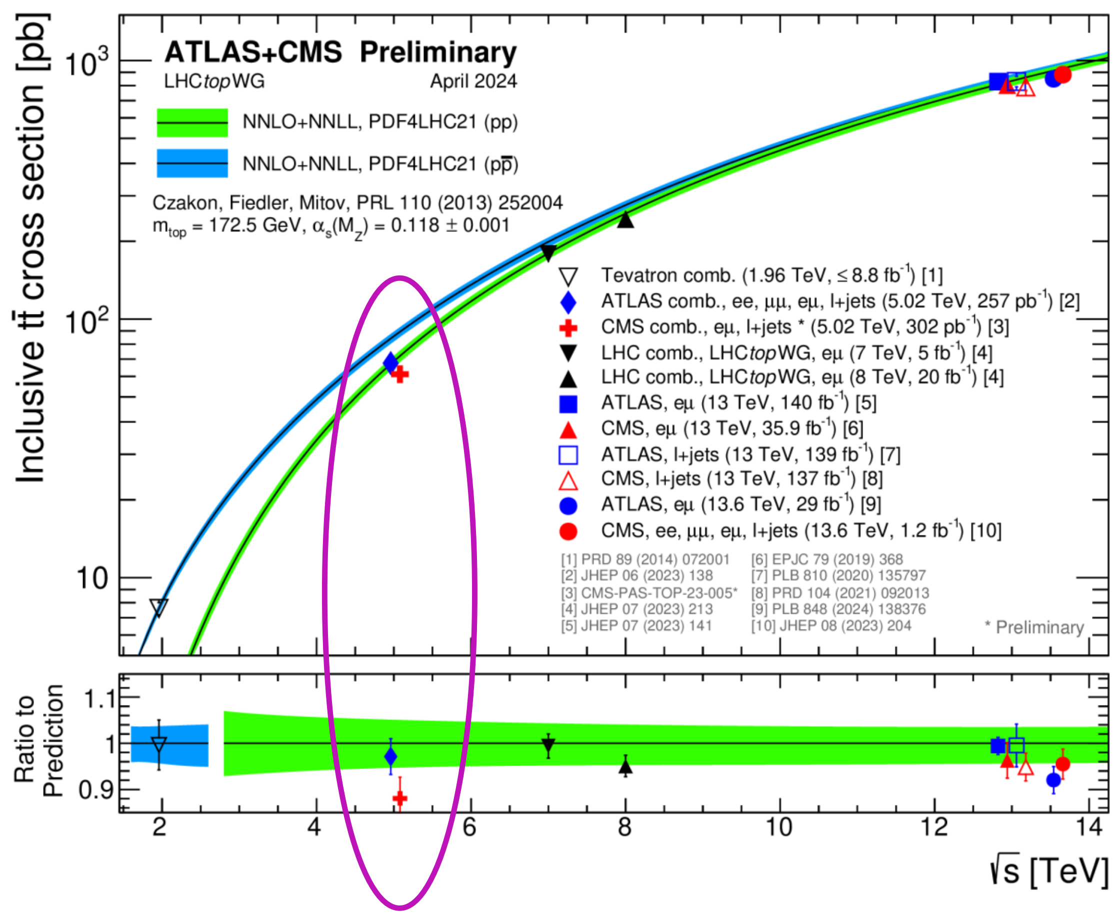
ttbar at √s=5.02 TeV: result

$$\sigma_{t\bar{t}} = 67.5 \pm 0.9(\text{stat.}) \pm 2.3(\text{syst.}) \pm 1.1(\text{lumi.}) \pm 0.2(\text{beam})\ \text{pb}$$

(3.9% precision)

- Result is consistent with the NNLO+NNLL QCD prediction of 68.2 ± 5.2 pb, and exceed the relative precision of theoretical calculations (7.6%)

- **Most precise single-lepton result in ATLAS**, even more precise than the 13 TeV result that used ~500 more data



ATLAS single-lepton result comparison using PLL

Uncertainty (%)	698 pb^{-1} @ 7 TeV	20.2 fb^{-1} @ 8 TeV	139 fb^{-1} @ 13 TeV	257 pb^{-1} @ 5.02TeV
Electrons	1.6	1.4	0.6	**1.2**
Muons	2.3	1.4	0.5	**0.2**
Jets	2.0	1.1	2.6	**1.1**
Flavour tagging	-	0.7	1.3	**1.1**
Generator	3.0 *)	1.1	-	**1.0**
Parton shower	0.5 *)	1.3	2.9	**0.9**
W+jets bgd	0.5	1.1	2.0	**2.4**
Total systematic	5.0	5.7	4.6	**4.2**

*) evaluated outside the fit

698 pb^{-1} @ 7 TeV: ATLAS-CONF-2011-121 (2011)

20.2 fb^{-1} @ 8 TeV: Eur. Phys. J. C 78 (2018) 487

139 fb^{-1} @ 13 TeV: Phys. Lett. B 810 (2020) 135797

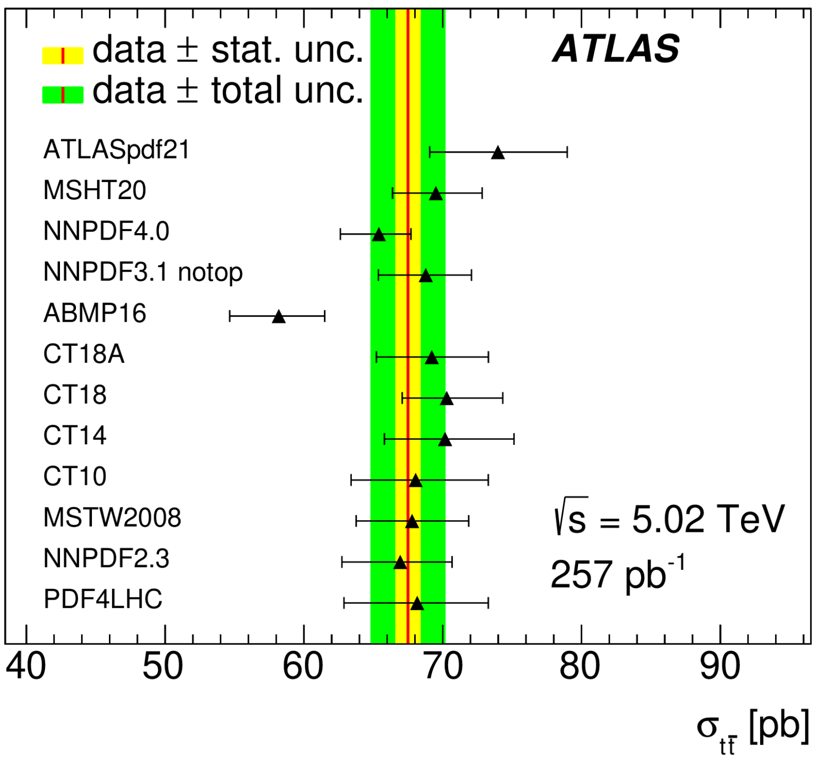
ATLAS single-lepton result comparison using PLL

Uncertainty (%)	698 pb^{-1} @ 7 TeV	20.2 fb^{-1} @ 8 TeV	139 fb^{-1} @ 13 TeV	257 pb^{-1} @ 5.02TeV
Electrons	1.6	1.4	0.6	**1.2**
Muons	2.3	1.4	0.5	**0.2**
Jets	2.0	1.1	2.6	**1.1**
Flavour tagging	-	0.7	1.3	**1.1**
Generator	3.0 *)	1.1	-	**1.0**
Parton shower	0.5 *)	1.3	2.9	**0.9**
W+jets bgd	0.5	1.1	2.0	**2.4**
Total systematic	5.0	5.7	4.6	**4.2**

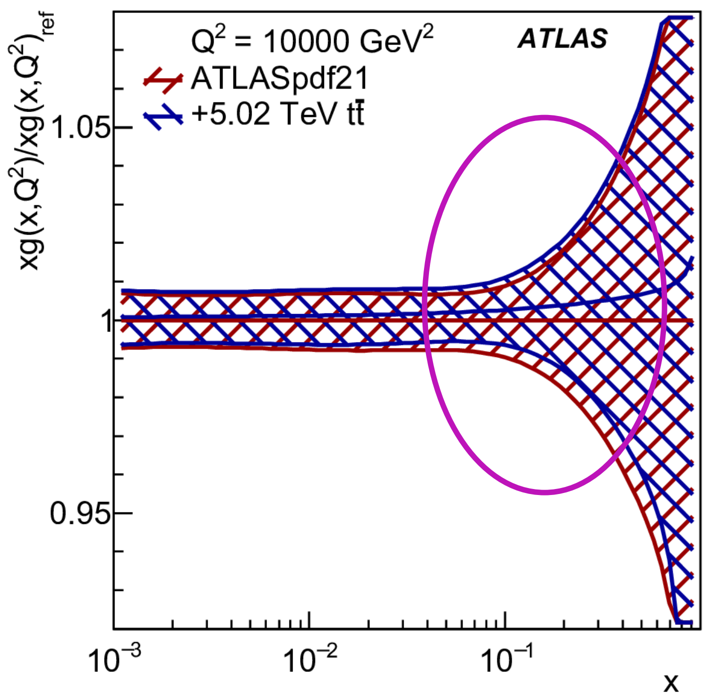
V.S. **V.S.O.P.** **X.O.** **Hors d’âge**

ttbar at $\sqrt{s}$=5.02 TeV: PDF reduction

- The measured value is compatible with the predictions of several parton distribution functions (PDF) considered, except ABMP16 (expected since has softer gluon PDF and predicts lower cross-section)



- Addition of new data shows a **5% reduction in the gluon PDF uncert.** in the region of Bjorken-x of 0.1



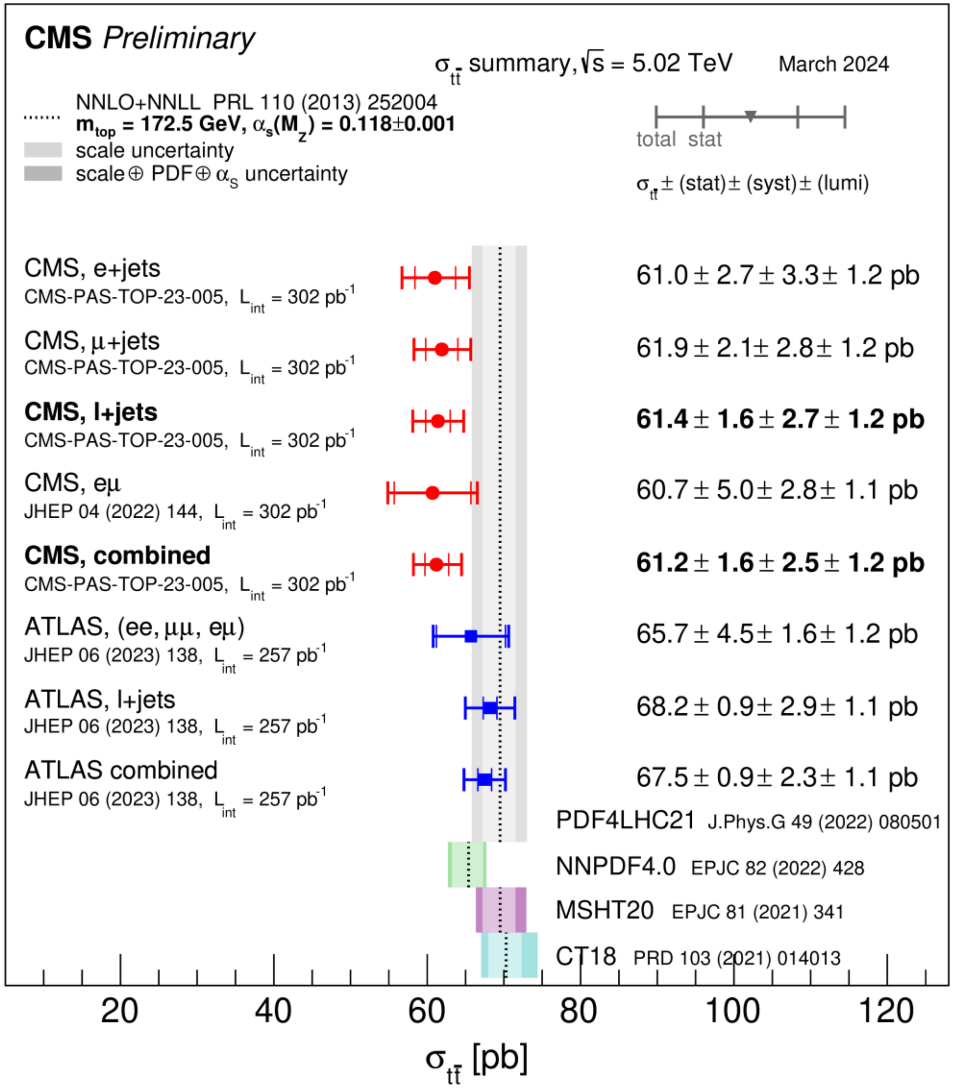
ttbar at √s=5.02 TeV: new results from CMS!

- CMS just released (**Abril 2024**) a new result in the single-lepton channel, and a combination with previous dilepton result

- Also using a multivariate analysis technique and applying a jet energy scale correction!

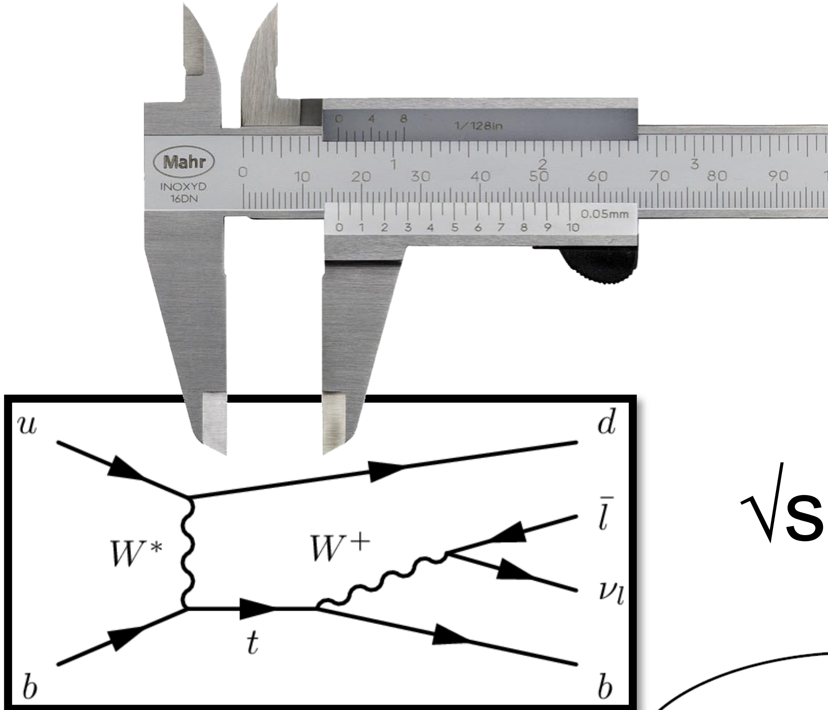
- CMS measures a combined σ(tt) of 61.2 ± 3.2 pb (**5.2% precision**)

- In agreement with the SM prediction and with previous measurements from CMS and ATLAS!

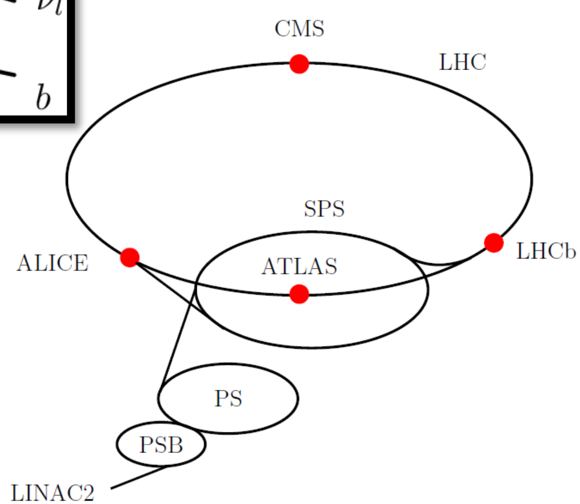


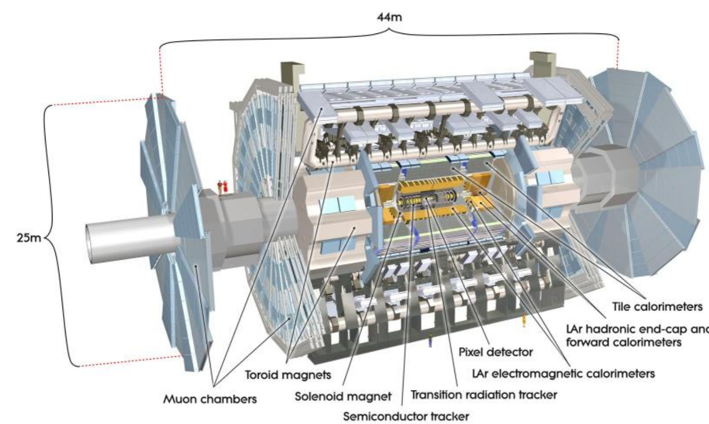
First ever σ(single top) at √s=5.02 TeV

Accepted past week to Phys.Lett. B!
https://arxiv.org/abs/2310.01518

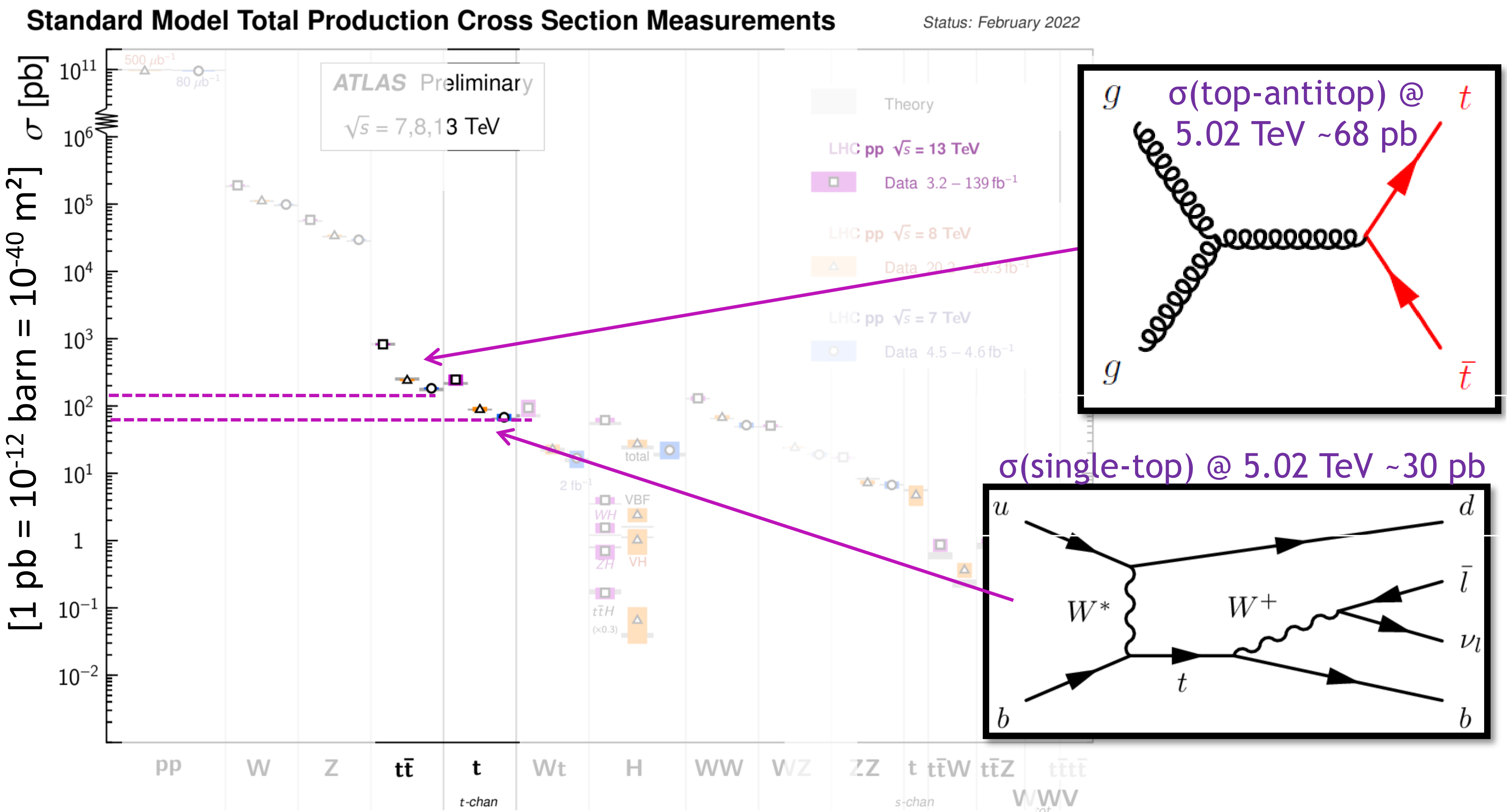


√s=5.02 TeV



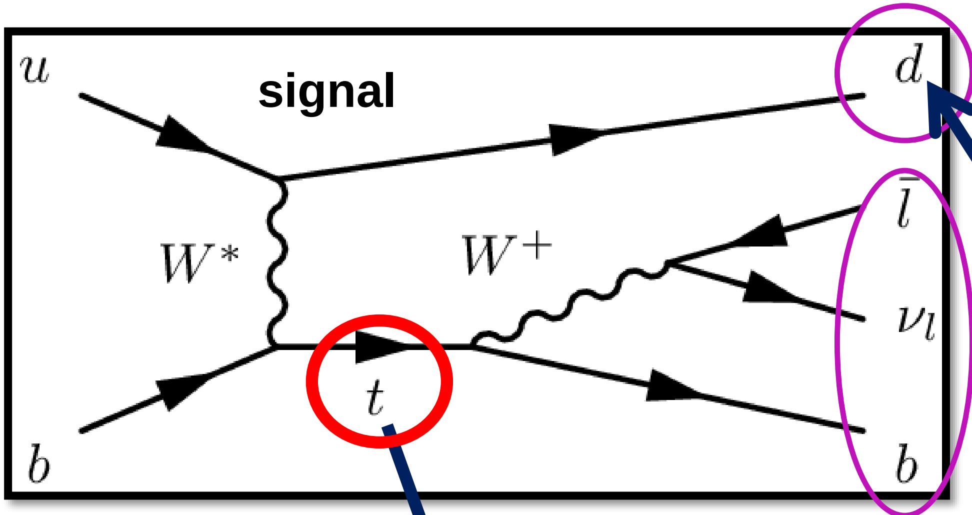


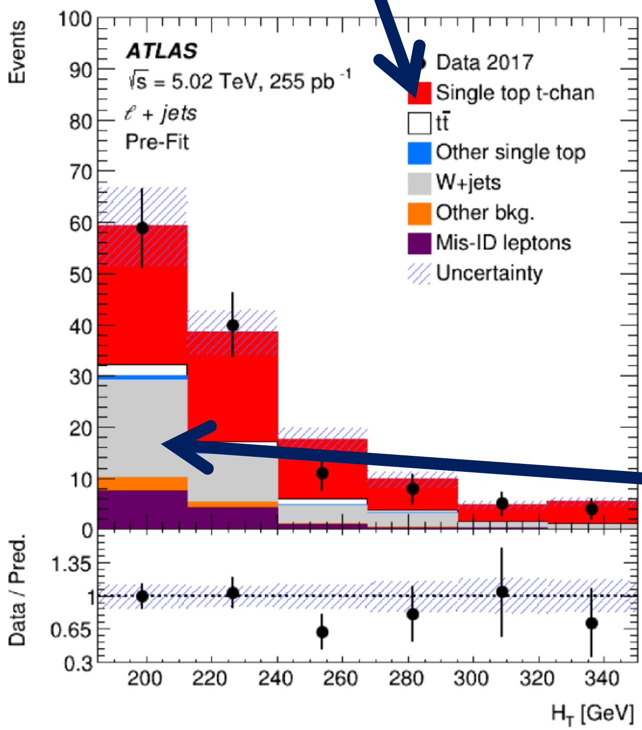
Single top quark production cross-section at the LHC



Single top quark via Electro-Weak production!

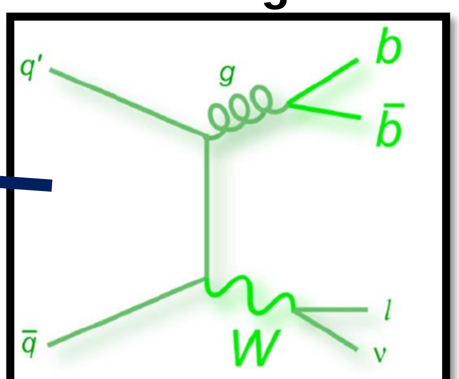
Finding single-top quarks in the single-lepton channel





- The single-lepton final state arising from single-top decay is characterised by one charged lepton, one neutrino, one b-tagged jet
- The **spectator-quark jet** tends to be produced in the forward direction!
- Select events that contain exactly one electron or muon candidate with pT > 18 GeV, exactly 2 jets, with b-jet with pT > 23 GeV and one forward light jet

main background



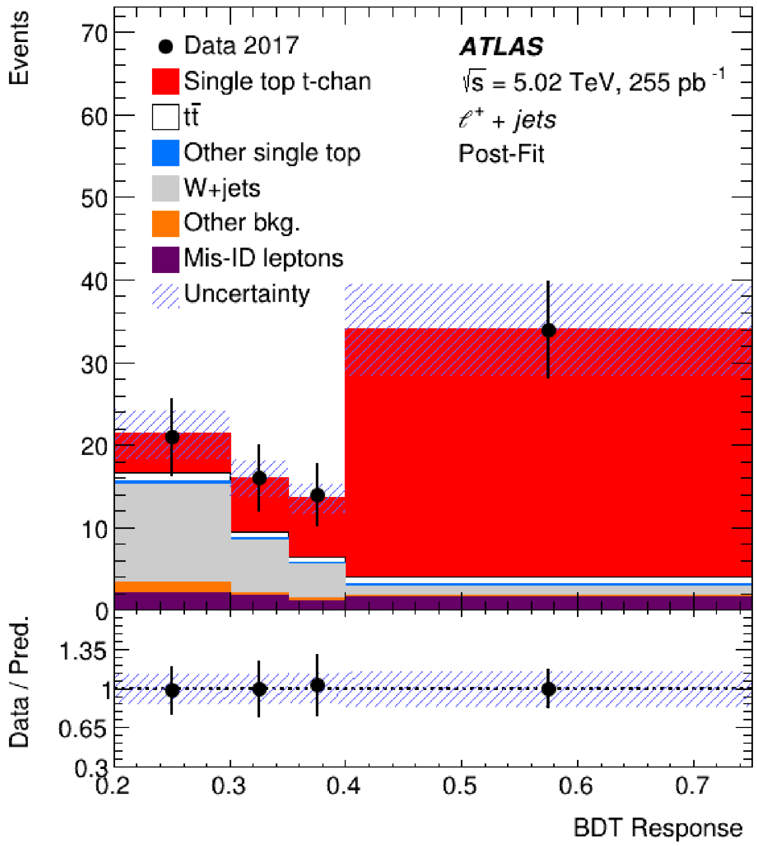
- Apply the same jet energy re-calibration as described previously, and port the systematic and fitting machinery from the ttbar analysis!

single top quark at √s=5.02 TeV: BDT

- Profile maximum-likelihood fit to the BDT discriminant distributions in two channels: lepton with positive and negative charges (single-top-quark and single-top-antiquark).

- Expected: **66 single-top events**!

Source	Number of events ℓ^++jets	ℓ^-+jets
$tq + \bar{t}q$	49 ± 9	17 ± 8
W + jets	23 ± 5	12 ± 3
Misidentified leptons	7 ± 3	7 ± 3
$t\bar{t}$	3 ± 0.5	3 ± 0.5
Z + jets and diboson	2 ± 1	2 ± 1
Other single-top-quark production	1 ± 0.2	1 ± 0.5
Total predicted	85 ± 9	42 ± 7
Data	85	42



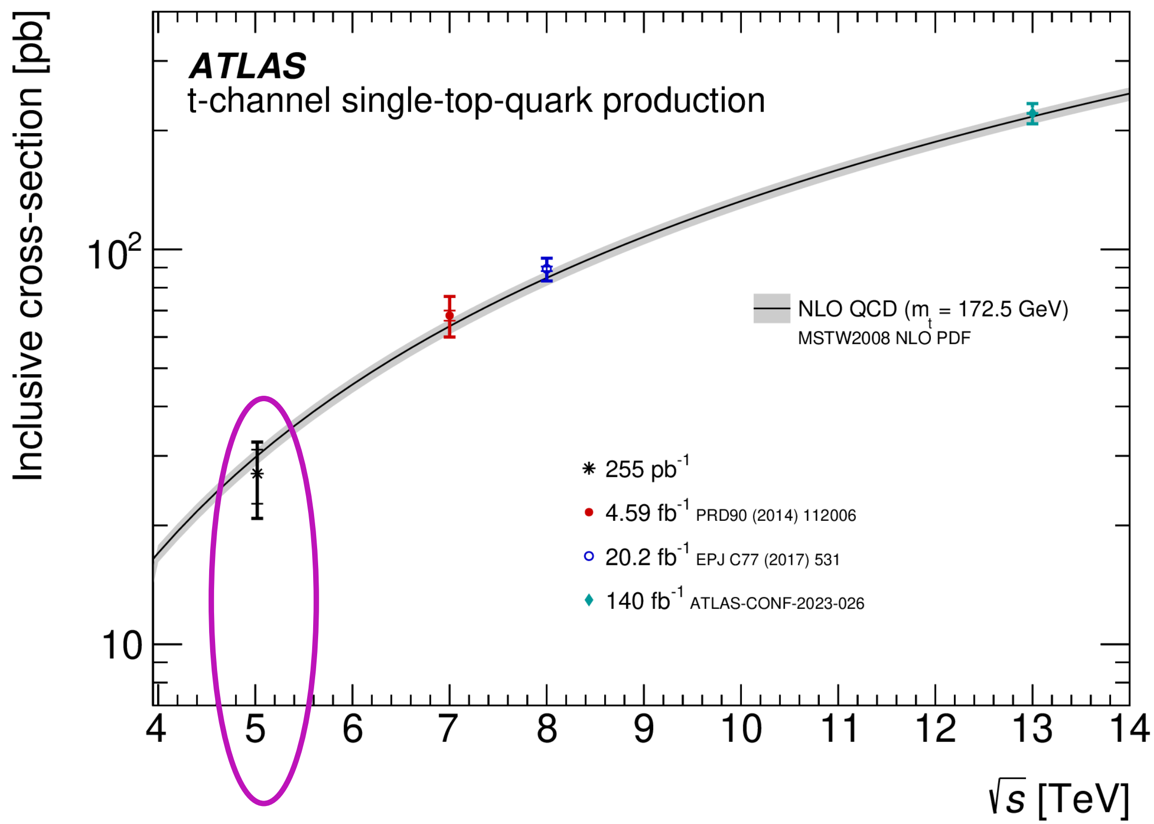
- We are observing the single-top production with a **6.1σ significance**!

single top quark at √s=5.02 TeV: result

$$\sigma(tq+\bar{t}q) = 26.6^{+4.3}_{-4.0}\ (\text{stat})\ ^{+4.4}_{-3.6}\ (\text{syst})\ \text{pb}$$

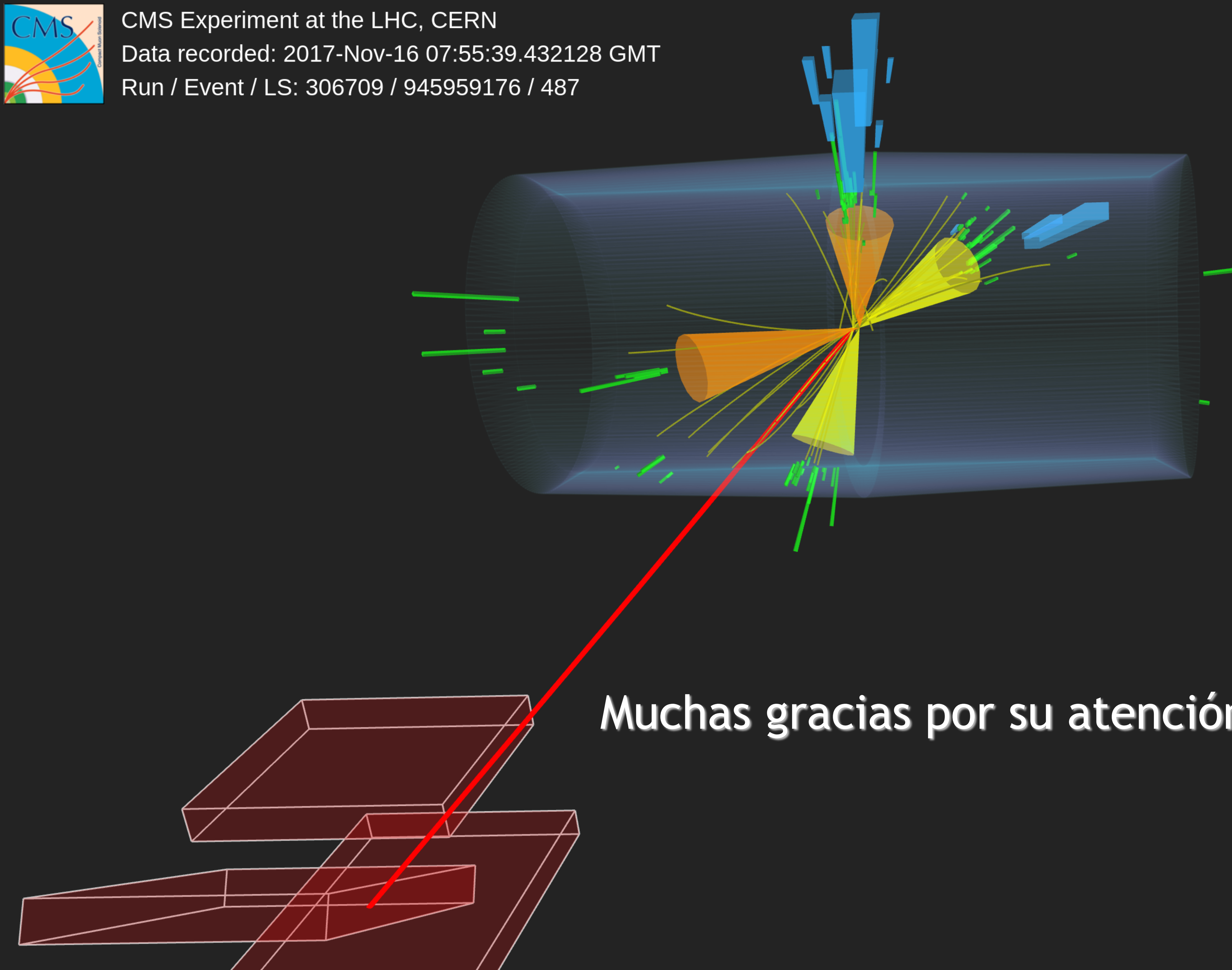
(22% precision)

- Result is consistent with the NNLO QCD prediction of 30.3 ± 0.6 pb
- **First ever measurement of the single-top production at this energy!**
- Provides another independent test of the SM predictions!



Conclusions

- **Inclusive σ(tt) is a standard candle at LHC**, allows us to test QCD predictions and constrain parameters such as top mass, α_S and PDFs.
- **Large statistics is not a guarantee of high precision** - we are limited by systematic uncertainties, both experimental and theoretical.
- High precision measurements require the use of different decay channels, optimisation of the analysis strategy, application of multivariate techniques and **careful assessment of systematic uncertainties** through detected object calibration.
- With just a **single week of data**, one can obtain results even more precise than those **using 3 years of data**.
- 5 TeV measurements of top quarks **bridge the gap** between the energy regime explored at the **Tevatron** (2 TeV) and the nominal **LHC** collision energies (7, 8, 13, 13,6 TeV), thereby testing the SM predictions in an intermediate regime.
- The good (or bad depending on your opinion): so far all the measurements are consistent with the SM prediction.



Muchas gracias por su atención!